Improved characterization through joint hydrogeophysical inversion: Examples of three different approaches

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With the increasing application of geophysical methods to hydrogeological problems, approaches for obtaining quantitative estimates of hydrogeological parameters using geophysical data are in great demand. A common approach to hydrogeological parameter estimation using geophysical and hydrogeological data is to first invert the geophysical data using a geophysical inversion procedure, and subsequently use the resulting estimates together with available hydrogeological information to estimate a hydrogeological parameter field. This approach does not allow us to constrain the geophysical inversion by hydrogeological data and prior information, and thus decreases our ability to make valid estimates of the hydrogeological parameter field. Furthermore, it is difficult to quantify the uncertainty in the corresponding estimates and to validate the assumptions made. We are developing alternative approaches that allow for the joint inversion of all available hydrological and geophysical data. In this presentation, we consider three studies and draw various conclusions, such as on the potential benefits of estimating the petrophysical relationships within the inversion framework and of constraining our geophysical estimates on geophysical, as well as hydrogeological data.

In the first approach, we use information obtained from radar tomographic velocity zones to invert tracer test data. We invert the hydrogeological field using non-stationary, unknown empirical petrophysical relationships and only use the information in the tomogram that helps us to fit the tracer test data. Synthetic studies are used to assess the effects of non-random errors in the intrinsic petrophysical relationships, and how geophysical data acquisition errors (e.g., unknown borehole deviations, unknown zero-times) affect our estimates. We conclude that we can estimate the spatial variability of the hydrogeological field given a strong intrinsic petrophysical relationships ($\rho>0.8$) and very carefully collected geophysical data. The results also illustrate the limitations of a sequential deterministic inversion approach.

In the second approach, crosshole ground-penetrating radar (GPR) travel times and hydrological measurements, collected before and during transient flow experiments, are used jointly to estimate flow parameter distributions in the vadose zone (and their uncertainty). This approach employs concepts from the Pilot Point method in a maximum a posteriori framework and requires the joint simulation of variably saturated flow and GPR travel times. In a synthetic 2D example, the permeability distribution is estimated, and additional parameters of the relative permeability and capillary pressure functions are estimated as well. The inclusion of GPR data in the inversion procedure is shown to be useful for estimating hydrogeological parameter distributions, and also for predicting breakthrough at a control plane. The strengths and limitations of the approach in a 3D setting are also explored through application to the Hanford field site (and specifically the Sisson&Lu Infiltration Site). Current efforts include extending the method to allow for estimation of petrophysical parameters, and also for estimation of geostatistical parameters.

In the third approach, we combine flowmeter test data and seismic travel time jointly to estimate the zonation of high and low permeability zones (and seismic velocity) at a uranium-contaminated fractured saprolite site managed by the DOE NABIR Program. We consider both the indicator of high permeability zone and seismic velocity at each location as random variables, and estimate those variables simultaneously by conditioning to flowmeter test data and seismic travel-time using the Gibbs sampling method. The approach allows us to estimate the probability of a high or low conductivity zone existing in a certain part of the interwell area. The parameters in the petrophysical relationships are unknowns, even though we assume that the structure of the relationship is given. Furthermore, we assume that the errors in the travel times are known and normally distributed. The study shows that a joint stochastic inversion approach can give us estimates of the permeability distribution that are better than the ones obtained by combining flowmeter data and tomograms. In addition, we make fewer and we get a meaningful uncertainty estimate.

Based on these three different examples of joint hydrogeological-geophysical data inversion, we conclude that a joint stochastic hydrogeophysical inversion procedure can improve parameter estimations and provide more meaningful uncertainty estimates than sequential deterministic methods. Each method offers different advantages and limitations, and were developed based on site-specific conditions and project objectives. A limitation to stochastic inversions is increased computational demands. However, this limitation is becoming less restrictive with increasing speed of computation and availability of parallel processing